Preparation of Aluminum Based Metal Matrix Composite by Thermal Spraying

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Abstract—*Metal matrix composites (MMCs) consist of a ductile matrix usually reinforced by ceramic particles or fibers. Compared to unreinforced alloys, MMCs offer a combination of diverse superior properties for various applications, as they have higher stiffness, strength, elastic modulus, improved wear resistance, and better fatigue resistance. This study provides a method of preparing aluminum based metal matrix composites (AMMCs) by High Velocity Oxy-fuel (HVOF) thermal spray technique. The study comprises the steps of providing the substrate; preparing a mixed powder comprising the matrix phase as pure aluminum (Al) and the dispersed phase as silicon carbide (SiC); preparing the bulk composite by using HVOF spray technique. The composites with different dispersions of SiC were prepared. The feasibly to make SiCp reinforced Al metal matrix composite by thermal spraying was studied successfully in this paper. An in-depth characterization of the composite formed has been performed by Optical microscopy (OM), X-ray diffraction (XRD), scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). Hardness of the composite prepared was measured on Vickers Microhardness Tester. The hardness of the composite has been found to increase with the increase in the reinforcement content.*

Keywords: *Aluminium Metal matrix composites, Silicon carbide, Thermal spraying, HVOF*

Introduction

Metal matrix composites (MMC) consist of a ductile matrix usually reinforced by ceramic particles or fibers. Compared to unreinforced alloys, MMC offer a combination of different, superior properties for various applications, as they have higher stiffness, strength, elastic modulus, improved wear resistance, and better fatigue resistance [1]. Aluminum metal matrix composites (AMMCs) have been widely studied in past decades and their use is now recommended in aerospace, automotive and electronic industries [2, 3]. These composites offer a large variety of mechanical properties depending on the chemical composition of the Al-matrix. They are usually reinforced by Al_2O_3, SiC, C but SiO_2, B, BN, B_4C, AlN may also be considered. Particulate metal matrix composites have been shown to exhibit significant improvements in certain physical and mechanical properties over their monolithic metallic counterparts. However, as the mechanical properties of the composite material are strongly dependant on the microstructural parameters of the system matrix-reinforcement, a judicious selection of a certain number of variables has to be achieved to optimize the properties of the composite [4].

SiC particulate reinforced aluminum matrix composites (SiC_p/Al) have been well developed in recent years, owing to their excellent properties such as light weight, high elastic modulus, wear resistance, low thermal expansion coefficient, and also due to possibility of their fabrication by many well-known methods [5]. Aluminium and silicon carbide, for example, have very different mechanical properties: Young's moduli of 70 and 400 GPa, coefficients of thermal expansion of 24×10^{-6} and 4×10^{-6}/°C, and yield strengths of 35 and 600 MPa, respectively. By combining these materials, e.g. A6061/SiC/17p (T6 condition), an MMC with a Young's modulus of 96.6 GPa and a yield strength of 510 MPa can be produced [6]. By carefully controlling the relative amount and distribution of the ingredients of a composite as well as the processing conditions, these properties can be further improved [7].

Thermal spraying is one of the most versatile surface engineering techniques available for the application of coating materials used to protect components from wear, erosive wear or surface fatigue and corrosion. In thermal spray processes, the deposited material is melted or heated by the combustion of gases, an electric arc or plasma. All these techniques permit the deposition of coating materials, generally ductile, with self-lubricating properties and improved corrosion and wear resistance [8]. One of the variants of thermal spraying namely High Velocity Oxy-Fuel (HVOF) has gained popularity in recent times due to its flexibility for in-situ applications and superior coating properties. The HVOF coatings have relatively low porosity, high hardness, high abrasive resistance, good wear resistance and the ability to resist many high-temperature corrosion environments [9-13]. The very high kinetic energy of particles striking the substrate surface does not require the particles to be completely molten to form high quality HVOF coatings (Voyer and Marple, [14]). HVOF spray technique has been used by many researchers to deposit composite coatings, but there is less available literature discussing the preparation and characterization of bulk metal matrix composites by this technique.

Therefore, in the current investigation attempts were made to prepare AMMCs with various dispersions of SiC by HVOF thermal spraying. Systematic study has been carried out to provide a method of preparing the composite. An in-depth characterization of the composite formed has been performed by Optical microscopy (OM), X-ray diffraction (XRD), scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) and are reported in the paper. Mechanical properties such as hardness and fracture toughness were also studied.

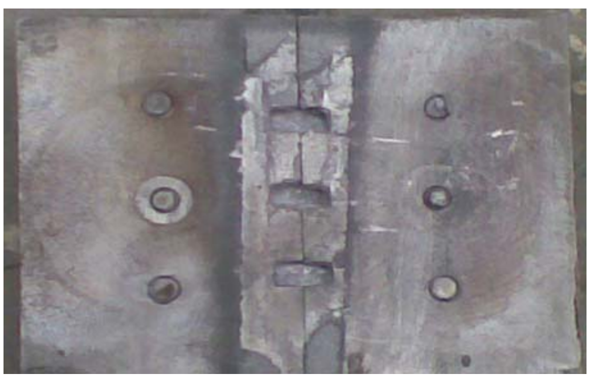
Experimental Details

Preparation of Substrate Material

Selection of substrate material was done after exhaustive literature survey. Die steel with composition of 1% C, 1% Mn, 5% Cr, 0.3% Ni, 1% Mo, and 0.3% V and remaining Fe for fabrication bulk material has been used as a substrate. The dimensions of the die steel were taken as 100 mm ×77 mm ×5 mm. Three rectangular equally spaced slots of 10 mm ×5 mm ×5 mm were cut about the transverse axis. The die was cut into two halves along the center line and is supported by a plate of dimensions 100 mm ×77 mm ×12 mm with 4 bolts and two aligning keys. This was prepared for the easy removal of the composite material (Fig. 1).

Powder Preparation

The 99.7 wt. % pure Al powder with an average size of 75 µm was used as a matrix material.



(a)

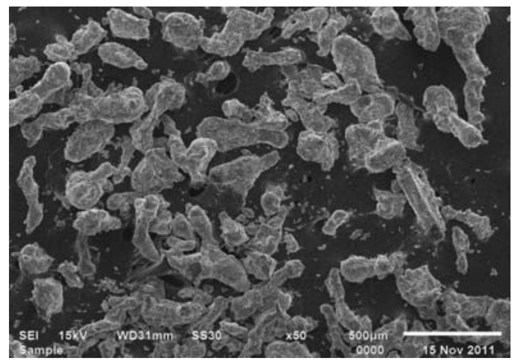
(b)

Fig. 1: (a) Die Steel Substrate Front View, (b) Rear View

The reinforcement material was SiC particles with an average size of 37.5 µm. SEM micrographs of the two powders are shown in Fig. 2. Two types of powder compositions namely Al-15%(SiC) and Al-20%(SiC) were selected for HVOF spraying on the substrate. Both the matrix and reinforced powders were mechanically alloyed by using ball milling apparatus for 6 hours. The matrix Al phase is mixed with the dispersed phase by weight. The mixing was performed at Metallizing Equipment Company Pvt. Ltd., (MECPL) Jodhpur. Ball milling conditions are shown in Table 1.

Table 1: Ball Milling Conditions

Mill jar	Stainless steel
Milling media	Stainless steel
Atmosphere	Air
Weight ratio of media to powder	10:1
Mill times	6 hrs



(a)

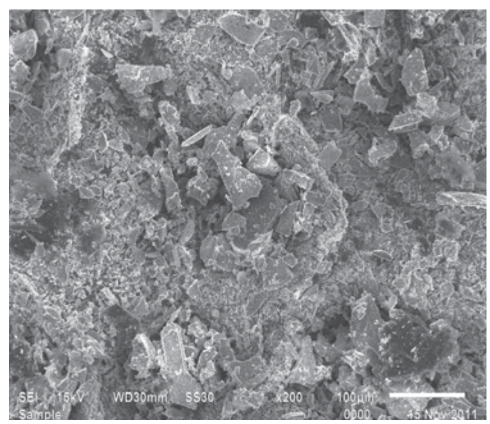


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Fig. 2: SEM Morphology of (a) Al Powder (b) SiC Powder

Preparation of Aluminum Based Metal Matrix Composite

The composites were then fabricated by HVOF thermal spraying at MECPL, Jodhpur (India) with their commercial HVOF (HIPOJET-2700) apparatus operating with oxygen and liquid petroleum gas (LPG) as input gases and nitrogen as carrier gas. The spraying parameters adopted for the HVOF spray process are given in Table 2. Composite thickness was kept in a range of 3±2 μm. After successfully obtaining the required thickness of the composite, the die was cooled with pressurized nitrogen gas and the difference in coefficient of thermal expansion resulted in easy separation of bulk material from substrate.

Table 2: Spray Parameters as Employed during HVOF Spraying

Oxygen flow rate (SLPM)	240–250
Fuel (LPG) flow rate (SLPM)	50–55
N_2 flow rate (SLPM)	15–20
Oxygen pressure (kg/cm^2)	9
Fuel pressure (kg/cm^2)	5.6
Powder pressure (kg/cm^2)	3
Spray distance (mm)	250

Characterization of the Prepared Composites

An in-depth characterization of the bulk composites was done by Optical microscopy (OM), X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS).

For metallographic studies, the specimens were first polished on a belt sanding machine having emery belt (180 grit). The specimens were then polished manually down to 1000 grit using SiC emery papers. Final polishing was carried out using cloth wheel polishing machine with 1 μm lavigated alumina powder suspension. Specimens were then washed and dried before being examined under Inverted Optical Microscope interfaced with imaging software Envision 3.0. Optical micrographs of the samples were taken by etching them with Keller's reagent (0.5 HF - 1.5 HCl-2.5 HNO_3 -95.5 H_2O).

X-ray diffraction (XRD) analysis of the samples was carried out using a Bruker AXS D-8 Advance Diffractometer (Germany) with CuKα radiation and nickel filter at 20 mA under a voltage of 35 kV. The specimens were scanned with a scanning speed of 1Kcps in 2θ range of $10^{o}$to 120^{o} and the intensities were recorded at a chart speed of 1cm/min with 2^{o}/min as Goniometer speed. The diffractometer interfaced with Bruker DIFFRAC plus X-Ray diffraction software provides'd' values directly on the diffraction pattern, which were further used for identification of various phases with the help of inorganic ASTM X-ray diffraction data cards.

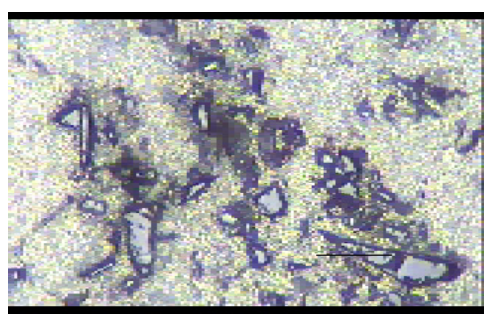
Surface morphology of the composites was studied on JEOL scanning electron microscope (SEM) equipped with energy dispersive spectroscopy (EDS). A microhardness tester (model-WILSON) with digital display was used to measure the microhardness of the prepared specimens. An indenting load of 300 gf was applied on the metal matrix avoiding ceramic particles. Three measurements were taken for each case to ensure the repeatability. Indentation load applied during the microhardness testing did not produce any sign of cracking to be measured and analyzed. Dwell time for indentation was taken as 10 seconds.

Results and Discussion

Optical Microscopy

The microstructures for the prepared bulk material as seen under an optical microscope are shown in Fig. 3. The microstructures for the composites with different proportion of reinforcements revealed the dense Al matrix with SiC particulates. Fig. 3 (a) with 15% SiC shows small and large SiC particles uniformly distributed in Al matrix. The reinforced particles are of irregular shape. Fig. 3 (b) with 20% SiC as reinforcement shows the clusters of SiC particles at various places in the Al matrix.

(a)



(b

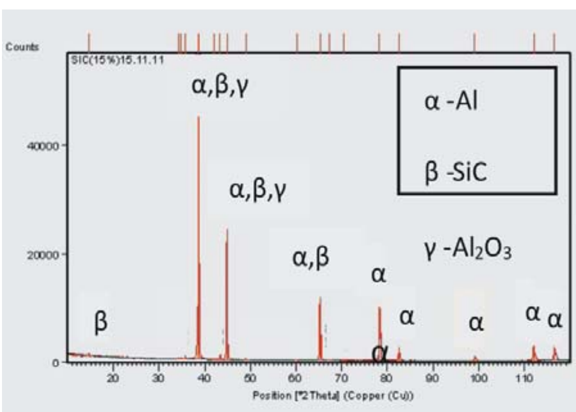
Fig. 3: Optical Micrographs of Composites (a) Al-15% SiC (b) Al-20%SiC

XRD Analysis

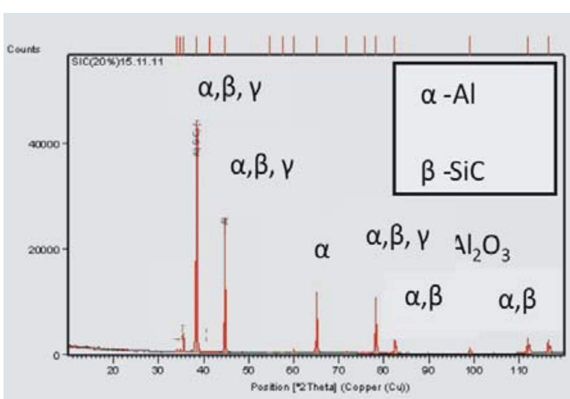
XRD diffractograms for the surfaces of the bulk material prepared by HVOF are shown in Figure 4 on reduced scales. For bulk material Al-15% SiC presence of aluminium as very strong intensity phase, SiC as a strong intensity phase and Al_2O_3 as a medium intensity phase was confirmed by the XRD analysis [Fig. 4(a)]. In case of Al-20% SiC the analysis shows formation of aluminium as very strong intensity phase. SiC and Al_2O_3 are identified as strong intensity phases [Fig. 4 (b)]. Khairaldien et al [15] developed Al/SiC composites by powder metallurgy route and further sintered the specimens at different temperatures. The authors also observed the formation of Al, SiC, Al_2O_3, and Al_4C_3 phases from X-ray diffraction patterns of two samples with 5% and 10% weight SiC sintered at 650°C.

SEM-EDS Analysis

The SEM morphology for the Al-15%SiC bulk material prepared by HVOF thermal spray process is shown in Fig 5(a). The bulk material is found to have splat-like morphology. The EDS analysis indicates the presence of mainly Al, alongwith C, O and Si. The analysis confirms the presence of aluminum and SiC particles in the composite fabricated by HVOF thermal spraying. The light grey phase was identified by EDS as aluminium and shining blackish grey phase is silicon carbide. At some places SiC particles are found trapped in the Al matrix. The splats are interconnected with each other at various places but they did not seem to form a continuous layer. Partial melting and oxidation of aluminum particles occur during the flight which is confirmed by presence of oxygen in EDS analysis.

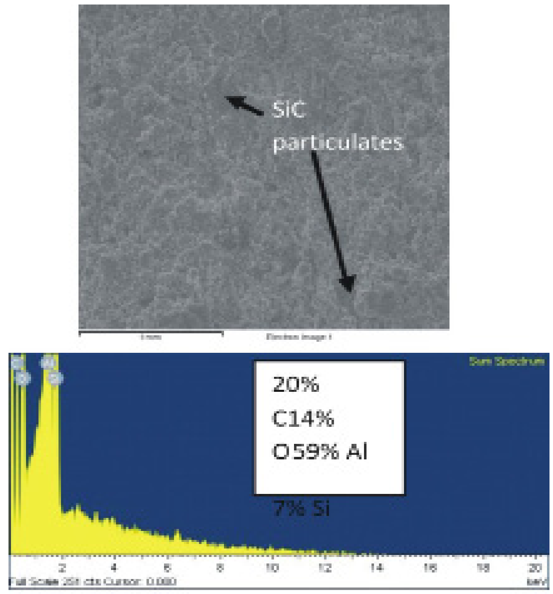


(a)

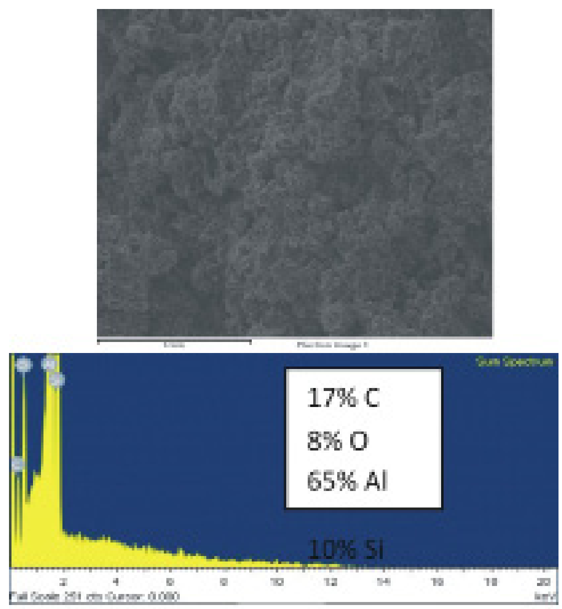


(b)

Fig. 4: XRD Diffraction Pattern for Composites (a) Al-15% SiC (b) Al-20%SiC



(a)



(b)

Fig. 5: Surface Scale Morphology and EDS Analysis of Composite Formed by HVOF Spraying Showing Elemental Composition (%) for (a) Al-15% SiC and (b) Al-20% SiC

The dense microstructure seems to be formed. This morphology is typical to HVOF spray process.

The surface morphology of Al-20%SiC bulk material [Fig. 5(b)] is also similar to that of Al-15%SiC bulk material with the difference that mesh splats are seen merged into each other, giving appearance of continuous surface layer at most of the places.. The EDS analysis shows the presence of mainly Al, alongwith C, Si and O. The analysis indicates the formation of a SiC in the composite. Torres et al [16] also found the splat like morphology on the surface of the as-sprayed Al-60% (SiCP) composite coatings on a mild steel substrate

Microhardness

Microhardness values were found on the Vickers microhardness tester. As expected, an increase in hardness was observed with the increase in reinforcement content in the composites. The microhardness values measured in the composite were found to be reasonably consistent implying nearly uniform dispersion of ceramic in the metal matrix. The microhardness values of the matrix phase of Al-15% SiC bulk material was in the range of 35.9-50.2 Hv with an average value of 46.16 Hv. The microhardness values for the material Al-20% SiC lies in the range of 39.8-55 Hv, with an average value of 48.5 Hv. Similar values have been obtained by other researchers.

Singla et al, [7] prepared Al/SiC$_p$ composite by stir casting technique by varying weight fraction of SiC (5%, 10%, 15%, 20%, 25%, and 30%). Hardness test was conducted by them on each specimen using a load of 250 N and a steel ball of diameter 5 mm as indenter. Diameter of impression made by indenter has been predicted by Brinell microscope. The hardness values of the composites formed with 15% and 20% SiC were found out to be 43.7 BHN (47Hv) and 44.4 BHN (49Hv) respectively. Bhattacharyyaa et al [17] fabricated a two layer functionally graded Al/SiC composite by powder metallurgy route by varying SiC from 10% to 20% and found out the hardness of composite. An indenting load of 25 gf was applied on the metal matrix avoiding ceramic particles. Hardness of composite layer having 20% SiC was found in range of 45-50 Hv.

Conclusion

1. HVOF thermal spray process has shown the possibility of making bulk metal matrix composites
2. Homogeneous dispersion of various phases has been observed on the bulk materials.
3. Prepared bulk material is totally free from any crack.
4. Blended composition was found to have splats like morphology where SiC and was seen distributed in an Aluminium matrix.
5. Hardness values of the composites found out to be in a range similar to those by other techniques.

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